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16. ABSTRACT

However remote the day when the first engineer constructed an artificial shelter against the elements and the vicissitudes of primitive life, it probably did not greatly antedate the period when Man also began the building of trails and paths.

A great deal has been written throughout the ages about roads and road construction. There are ancient accounts of roads which once led to the "grandeur that was Rome;" and in our own time the eulogistic advertising emanating from our Chambers of Commerce rarely fails to mention highways among the local assets. The increasing number of technical papers and publications dealing with the subject is even more significant of the modern trend, and is an indication of the scientific attitude which is becoming more and more a factor affecting the design of highways.

As road building has expanded with the advance of civilization, methods of design and construction have improved. In common with other sciences, most of the knowledge and advancement has been gained through trial and error, the method by which most progress has been made. There is little question as to the generous application of this method in highway construction, although one may sometimes wonder whether the trials have been as numerous as the errors. At any rate, in the United States today we find ourselves with a vast system of highways- federal, state and county- representing every variety of type and construction.

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A NEW METHOD FOR DETERMINING THE STABILITY OF BITUMINOUS PAVEMENT MIXTURES

A DEVELOPMENT AT THE LABORATORY

OF THE CALIFORNIA DIVISION OF HIGHWAYS

INTRODUCTION

However remote the day when the first engineer constructed an artificial shelter against the elements and the vicissitudes of primitive life, it probably did not greatly antedate the period when Man also began the building of trails and paths.

A great deal has been written throughout the ages about roads and road construction. There are ancient accounts of roads which once led to the "grandeur that was Rome;" and in our own time the eulogistic advertising emanating from our Chambers of Commerce rarely fails to mention highways among the local assets. The increasing number of technical papers and publications dealing with the subject is even more significant of the modern trend, and is an indication of the scientific attitude which is becoming more and more a factor affecting the design of highways.

As road building has expanded with the advance of civilization, methods of design and construction have improved. In common with other sciences, most of the knowledge and advancement has been gained through trial and error, the method by which most progress has been made. There is little question as to the generous application of this method in highway construction, although one may sometimes wonder whether the trials have been as numerous as the errors. At any rate, in the United States today we find ourselves with a vast system of highways - federal, state and county - representing every variety of type and construction.

The demand for improved highways, in common with most human wants and desires, has kept well ahead of the funds available for their construction. Not the least of the knotty problems laid at the door of the highway engineer concerns the designing of highway pavements that will be smooth, dustless, non-skid, economical to maintain, but, above all, inexpensive to build. Due to economy of first cost, the bituminous type of surfacing occupies a preferred position wherever this type will serve the traffic as well as a more expensive type.

I

Although numerous books, papers and treatises have been published in recent years dealing with one phase or another of bituminous paving construction, it is noteworthy that "The Modern Asphalt Pavement" by Clifford Richardson, published in 1905, was regarded for more than twenty years as the best authority on the subject. Within the last decade, however, there have been many independent studies, and a number of investigators have propounded new rules for guidance, or have designed testing equipment to measure qualities believed to be important.

Of all the qualities of bituminous pavements which have been the object of research, that of stability has probably received more attention than any other. Machines for testing stability have been designed by most of the leading asphalt technicians, including Besson, McNaughton, Howe, Abson, Uhlman and Milburn, Emmons and Anderton, and Hubbard and Field. That the solution of the problem of correctly measuring relative stability is elusive is evidenced by the number and variety of testing devices, and from the rather widespread disagreement as to their applicability.

It is the purpose of this article to describe still another stability testing machine which has been developed in the Materials and Research Department of the California

Division of Highways, together with such evidence as is now available concerning its relation to pavement behavior. To judge from the writings of those who have been occupied with the problem, most of the stability measuring devices have been designed for mixtures of the sheet asphalt or asphaltic concrete type, in which the binding medium consists of a relatively hard asphaltic cement; and research, for the most part, has been applied to bituminous mixtures which have long been conventionalized. Mixtures such as sheet asphalt and asphaltic concrete fall within a rather narrow range of grading tolerances, character of aggregate, and grade of asphalt, and the bulk of investigations which have led to the design of stability testing apparatus have been based on a study of such pavements.

II

The chain of circumstances which led to the development of the California type machine has had some bearing upon its form, and a brief outline of these circumstances may be of interest. The need for extended mileage of surfaced roads and the failure of funds to keep pace with the demand, led to the development and rapid growth of the oil mix type, a number of variations of which are classed under the general heading of bituminous treated surfacing.

In the beginning, this type of surface was of the light oil mixed-in-place type, and was constructed by state forces, using maintenance equipment, and utilizing local material or road metal already in place. Mixing was done with graders and harrows after the application of road oil from truck distributors. Many miles of highways have been surfaced with some variation of this procedure, and in most instances have left little to be desired in the way of smooth-riding surfaces with low maintenance and low construction costs.

In spite of the generally successful results obtained with early road-mix and later plant-mix methods, there were nevertheless several instances where the results were not satisfactory. It was soon found that roads of this type occasionally became unstable or showed failure in several ways, from reasons not always clearly evident. In fact, when failures did occur, the opinions as to underlying causes were as varied and numerous as the observers themselves.

In 1929, the third year of oil mix construction in California, an investigation was conducted to ascertain the causes of failure of several of these roads.

As might be expected, a number of causes were found to contribute to failure of oiled road surfaces, and in common with experience in Arizona and other western states it was soon found that the relative "affinity" of the aggregate for oil or for water is a very important factor.

Tests to measure this quality were adopted, and by means of the "Swell Test" on compacted specimens and the "Water-Asphalt Preferential Test" on filler dusts it has been possible to eliminate most aggregates which show a tendency toward preferential adsorption of water in the presence of asphaltic oil.[1,2.]

As may be readily appreciated, the first requisite for a successful investigation of this sort is the use of test methods and equipment which will measure and clearly evaluate the qualities contributing to success or failure. Therefore, as an essential preliminary step, it was necessary to adopt some means of measuring stability in order to compare this quality between different sections.

III

There were then available two stability testing machines designed for asphaltic mixtures, one applying a load resulting in a direct shear stress, and the other developing a more complex shear which results in extrusion of the specimen.

Samples of oil mix surfacing which had been known to withstand traffic successfully gave results so low in these testing machines as to be almost negligible when compared to standards considered acceptable for asphaltic mixtures.[3] Inasmuch as these oil roads had successfully withstood traffic of automobiles and trucks similar to those operating on high-type pavements, it appeared reasonable that a proper stability test should accord them qualities substantially as high as those displayed by satisfactory asphaltic concrete mixtures, and, furthermore, should be even higher than an asphaltic concrete mixture which has proved to be unstable by waving and rutting under the action of traffic.

Upon studying various sections of the oil mix roads it was observed that the aggregate in those showing distress seemed frequently to be of harder, smoother rock particles than the aggregate in roads remaining smooth and stable under traffic. This aroused speculation as to the inherent differences in mineral aggregates, particularly their tendency to resist displacement or internal movement under load.

It appeared that certain aggregates in a dry, uncompacted state could be expected to move and displace readily under a superimposed load, individual particles sliding or rotating, or shifting in a combination of movements. Other aggregates (generally having particles of a rougher or more irregular surface texture) apparently displayed much less disposition to move or be displaced laterally under an applied load.

Seeking means to measure this quality, it was postulated that if a cylindrical container were filled with a mixture of aggregate and a load applied to the surface of the mixture, the pressure transmitted to the side walls of the container would vary inversely with the internal friction of the mass.

In pursuance of this idea, early in 1930 a split metal cylinder was constructed so that any pressure tending to expand the side walls could be measured. This apparatus was somewhat crude, but gave clear indication that mineral aggregates without bituminous binder varied considerably in their capacity to absorb loads by internal friction.

Hard, polished particles such as quartz gravel or Ottowa sand transmitted the greatest amount of pressure perpendicular to the applied load, whereas crushed rock having obviously rough surfaces with a sandpaper-like texture transmitted the least amount of pressure.*

As a further illustration, it is obvious that a liquid will transmit pressure to the side walls per unit area equal to the applied load per unit area; whereas, in the case of a solid block of stone, concrete or steel, there will be no appreciable horizontal reaction, except under extremely high loads.

*The general agreement as to the superiority of crushed rock compared to most stream gravels is proof that this quality has long been recognized.

IV

At this point, it will be well to approach the problem from another angle, and consider conditions in an actual pavement, in which the presence of a bituminous binder of some kind holds the rock particles in place.

In the case of "D" grade and harder asphalts, this binder has been referred to as "asphaltic cement," implying that the bituminous binder cements the rock particles together and imparts a resistance strength to the mass in a manner similar to the action of Portland cement in hydraulic concrete. It has been the frequent tendency in the design of asphaltic pavements to meet the stability requirement by specifying harder asphalt, such procedure being based on the assumption that the asphalt is responsible for the stability of the mixture.

The well known tendency of low penetration asphalt to become undesirably brittle in cold weather, and the fact that pavements in which even "C" grade asphalt is used are not always free from distortion in warm weather, proves that this assumption is true only to a limited extent. Skidmore[4] has noted that pavements built with soft asphalt may remain stable for a long period, and considers the character of the aggregate of considerable importance.

A frequent impression is that asphaltic pavements are roughened and distorted by the <u>driving</u> action of vehicle wheels. Any such conclusion, however, appears unwarranted. It may be observed that rutting is due to lateral displacement; and, furthermore, that waves or ripples usually accumulate in the direction in which traffic is moving. Mr. Perkins,[5] of the Warren Paving Company, has made some excellent observations, which seem to be in entire agreement with the facts observed elsewhere. If further proof is necessary, reference may be made to the experimental work carried on by the United States Bureau of Public Roads, reported by W. J. Emmons and B. A. Anderton,[6] in which the displacement of a bituminous surface was indicated by the forward movement of brass screws or plugs in the direction of traffic.

In analyzing the action responsible for this distortion, it is obvious that the prime force is the weight of the vehicle. The vehicle tends to sink into the pavement surface, and when in motion pushes forward in front of the wheel one side of the depression thus formed. Presumably, in a perfectly uniform and homogeneous mixture, and with the vehicle traveling at a uniform rate and constant speed, any wave or ripple thus formed should proceed ahead of the vehicle indefinitely, or at least for the complete length of the pavement.

Bituminous pavements are rarely of uniform quality, however, nor do vehicles proceed at uniform speed. Several factors probably contribute to the formation of transverse waves or ripples* which may become quite extensive and of considerable magnitude under certain conditions.

Figure 1 shows a diagram of a pavement surface, with a loaded wheel displacing a small wave or ridge in the direction of travel.

Figure 2 is a diagram illustrating the probable movement within the mass of the pavement under load. There is ample evidence, both experimental and theoretical, that the effect of a load on a plastic surface tends to force downward a conelike or wedge-shaped body of the material.

From a study of the diagram Figure 2, it is evident that distortion or flow in a plastic solid, in which the loaded area covers only a small portion of the exposed upper surface, consists of a cone-shaped mass of the material being forced downward, meeting the resistance of an adequate support (subgrade), and the resultant forces are diverted horizontally and radially against the surrounding mass outside the loaded area. The lines of least resistance naturally trend upward toward the unloaded surface surrounding the loaded area, so that when the load exceeds the resistance of the plastic solid, an upheaval occurs around the loaded area.

*Not to be confused with the "wash board" ripples formed on earth or fine gravel roads by the harmonic abrasive action of high speed vehicles.

In producing the movement thus described, work is done principally in overcoming friction between the solid particles of the mass, and partially in overcoming adhesion in certain areas. (This last resistance varies with the speed of action.) The pressure horizontally transmitted to the side limits of the prism beneath the load will be less per unit area than the load pressure applied, so long as any internal friction exists.

In the case of a loaded vehicle on a bituminous pavement, the area covered by the wheel is relatively small compared to the total area of the pavement (the loaded area is approximately oval and say 4 inches by 8 inches in diameter, depending on tire size, etc.). The portion directly under load is then represented by a prism with an upper surface corresponding to the loaded area, and with a depth equal to the depth of the pavement.

If this prism were a solid having the characteristics of concrete or steel, there would be no appreciable lateral movement under any stress within the range of vehicle loads.

In the case of bituminous pavements, however, there is a distinct tendency for the loaded area within the body of the pavement to bulge outward. (Isolated specimens or cores will assume a barrel shape under load.)[7] The pressure per unit area tending to expand the sides of the loaded cylinder will vary with the internal friction, and in all bituminous pavements will be less per square inch than the applied load.

This transmitted pressure encounters the resistance of the surrounding mass of pavement outside the confines of the loaded area, and develops further similar lines of shear.

If movement takes place, it will be in the direction of least resistance, or upward toward the unloaded surface outside of the load area. The application of surcharge loads on unstable foundation soils illustrates that the pressure thus transmitted through a plastic material having some internal friction may be balanced with a surcharge (i.e. - superimposed load) of considerably lower magnitude than the main load.

It seems evident that the distribution of the load to the subgrade cannot be uniform, but will be greatest directly under the center of the loaded area, and will diminish outward in varying degree, depending on the character of the pavement. The pressure on the subgrade outside of the loaded area cannot greatly exceed the upward pressure tending to distort the surface of the pavement (action and reaction being equal). A consideration of Goldbeck's[8] bearing value investigation made with the use of pressure cells under varying depths of gravel surfacing will be interesting in this connection.

In designing a testing machine to measure the flow of plastic materials, it must be recognized that the prism directly under the loaded area of an extensive pavement slab is held in place and particles kept in close contact by the pressure or lateral support of the surrounding mass of pavement. For this reason, tests on briquettes performed in a manner similar to the testing of concrete specimens are not very illuminating, because very light loads produce distortion, and particles once displaced have very little resistance to further movement. It would seem essential that any testing machine should furnish lateral support to the specimen, at the same time permitting motion, and measuring the tendency to move against such support.

V

APPARATUS FOR MEASURING STABILITY OF BITUMINOUS MIXTURES

Required: A testing apparatus that will subject test specimens to stresses similar in magnitude and direction to those occurring in pavements under traffic.

Means for recording results in order to measure "stability;" i.e., resistance to distortion or rutting and waving of the road surface.

Test specimens should be of sufficient size to permit the use of aggregate up to the maximum size used, or at least one-inch stone. To be representative, specimens should be tested using aggregates with the gradings used in the actual pavement. It should be possible to test specimens artificially compacted in the laboratory or cores cut from the roadway surface.

Hypothesis

Mixtures of sand, crushed stone or gravel, and any bituminous binder, constitute a binary system of solid particles coated with a viscous liquid. Such a system is a plastic solid. The degree of plasticity or mobility of the mass will vary with the character of the surfaces of the solid particles and with the pressure applied, so long as the viscous liquid is not present in sufficient quantity or consistency to separate the solid particles.

When an excess of liquid or lubricant is present, liquid friction will be substituted in greater or less degree in place of solid sliding friction, and the mass will deform or change shape more readily.

If the liquid is very viscous, the deformation will be relatively slow. If it is of low viscosity, the change may be rapid. In any event, when liquid friction alone is to be overcome, the load need not be great if sufficient time is allowed.[9]

The desirable end in a bituminous pavement is to cause the bearing surfaces (i.e. - the solid mineral particles) to seize and thus develop the actual strength of the rock rather than the much lower surface resistance when sliding in a viscous medium.

Asphaltic pavements frequently become wavy and rutted without any break or fracture of the surface; therefore, any test method designed to measure the load required to break or rupture the specimen may not be measuring the essential quality.

It is generally recognized that bituminous pavements are most liable to deform during extreme hot weather, and for this reason a temperature of 140°F. has been generally adopted for the test temperature. Observations indicate that the temperature of black pavements under the direct rays of the sun will be from 25 to 35 per cent higher than the atmospheric shade temperature.[10]

It has also been noted that bitumens will deform or change shape under very light pressure if the load is applied for a sufficient period of time. The amount of deformation will bear a direct relation to the time or duration of the stress, and does not vary directly with the load.[11]

Considering all the above facts, it appears that the behavior of a test specimen under a slowly applied load at a critical temperature, say 140°F., should show the behavior of a bituminous mixture in the most susceptible or vulnerable condition which may be expected in actual service.

Asphaltic paving mixtures may be classed as plastic solids; hence, a measure of resistance to plastic deformation should be a measure of stability.

The degree of roughness or distortion of the pavement is the accumulated result of a large number of quick shoves or pushes,[12] each one lasting for an infinitesmal fraction of time. The pressure exerted by vehicle tires has first to overcome any friction between the particles of mineral aggregate. The residual forces (load minus frictional resistance) cause movement varying according to the rate at which the particular bituminous binder will flow under the prevailing conditions (of temperature, amount and consistency of the asphalt, amount of filler dust, etc.).

If the bituminous binder flows or displaces an amount N under load L and time T, then under traffic (equivalent to the load L) the displacement N will be reached when the sum of the effective duration periods of the individual pushes equals the time T.

$$N = f\ (LT)$$

It appears that the deformation under load will vary approximately in direct ratio with time but not in direct ratio to the load when a viscous liquid is involved.

The equipment designed to measure resistance to lateral deformation under load has been termed the "Stabilometer."

Description and Operation

The Stabilometer is a form of plastometer, and consists essentially of an outer metal shell of cylindrical form within which is secured a rubber tube of smaller diameter.* The rubber is clamped to the cylinder at each end in such a manner as to form a water-tight chamber between the outside of the rubber tube and the inner side of the metal cylinder. This water-tight chamber is filled with any suitable liquid, and connected with a pressure gauge to register the pressure to which the

*The first model was a metal cylinder, cut to permit expansion. The accuracy of this type was not satisfactory, however.

liquid is subjected.

A compacted test specimen is formed to fit snugly within the rubber tube, and any lateral expansion of the loaded test specimen transmits pressure to the liquid through the flexible rubber walls and the resulting pressure is recorded by the test gauge.

Laboratory test specimens may be prepared by tamping, compression, or any suitable means of compaction so adjusted as to give the same efficiency of consolidation as is obtained from rolling or traffic, which is not necessarily accurately indicated by density. Specimens cut from the pavement with a core drill should be of proper size to fit the Stabilometer.

With the test specimen in place, the liquid in the surrounding hydraulic cell is brought to a standard initial pressure by means of a hand-operated displacement pump. This initial pressure forces the rubber walls into snug contact with the side of the specimen before the test load is applied. The initial pressure must be maintained uniform for all specimens if direct comparison is desired.

The Stabilometer is then placed on a testing press of either the beam or hydraulic type, and the load is applied at any desired speed, preferably a slow head speed of 0.05 inches per minute. (A. S. T. M. standard for concrete compression tests.) The load is applied over the entire surface of the compacted briquette, and the resultant pressure tending to deform the specimen at right angles to the direction of the test load is transmitted through the rubber walls and registered by the pressure gauge of the Stabilometer.

A frictionless liquid specimen would transmit pressure per unit area equivalent to the applied load per unit area. An absolute solid would transmit no pressure. Plastics or semi-solids will, of course, range between the liquid and the solid.

Test results may be interpreted in various ways, as for instance the ratio of transmitted pressure to the applied pressure, by comparing the amount of load absorbed in overcoming resistance of the specimen, or by referring to an arbitrary scale in which zero will represent a frictionless liquid condition, and one hundred per cent a rigid solid.

Tests may be performed on any sort of stiff plastic material, such as clays, soils for bearing values, waxes, aggregates with or without bituminous binder, and, with certain modifications, may furnish a practicable means of measuring the plasticity or workability of concrete mixtures.

The machine described is, of course, the result of considerable experimental work and has been improved and modified with experience. It has been adopted by the Materials and Research Department of the California Division of Highways as a routine test for bituminous mixtures of the oil mix or cutback type, and in this connection has probably been applied to six or seven thousand specimens, most of which were compacted by artificial means in the laboratory.

In applying the Stabilometer to samples of oil mix pavement, it is necessary to prepare specimens by artificial compaction in the laboratory. The weak binding medium does not, in most cases, permit the cutting of cores from the pavement.

Tentative limits were established based on a few observations, and during the application of the test to current work, results have been studied in order to arrive at more correct correlation. Stability results have been reported in a scale ranging from 0 to 100 per cent, in which 0 would equal a liquid condition, and 100 per cent would be the equivalent of a solid with no measurable lateral reaction under the test loads employed.

A study of the United States Bureau of Public Roads report on the impact effect of vehicles[13] and the State of Pennsylvania investigations of tire pressures with the sectometer[14] led to the assumption that a test load equivalent to approximately 400 pounds per square inch would be reasonably representative of the stresses developed by pneumatic tired truck traffic (recognizing the increase of static load due to so-called impact).

Test results are compared by means of the Stabilometer reading at 400 pounds per square inch, and correlation with pavements under actual traffic indicates that a stability value between 30% and 35% represents the borderline condition. In other words, stability values less than 30% indicate a pavement which will invariably displace under traffic, while pavements having stability values above 35% have so far indicated a satisfactory surface. The volume and type of traffic, of course, vary sufficiently between different sections of pavement so as to make a precise agreement difficult.

In order to determine its applicability and establish close correlation with field work, a number of cores have been taken from existing asphaltic concrete pavements. The pavements were classified by inspection as either stable or unstable. Such visual comparisons are necessarily very inexact. The most that could be expected would be that stability test results would show a preponderance of low values in any unstable group, and a preponderance of high values in the stable pavements. Variation in pavements due to segregation on the street, and difficulty in selecting a typical area to be sampled, all render it impossible to obtain precise agreement.

VI

The first tests with the Stabilometer were made on specimens of oil treated aggregate. As work continued, it became evident that test results were in good correlation with the stability evidenced by pavements under traffic. After a time, specimens of cutback asphalt mixes and asphaltic concrete were tested, and also laboratory mixtures were prepared in which the quality of the aggregate and the grading were maintained constant, the only change being in the consistency of the asphalt.

It was found that the Stabilometer gave practically identical results with a given aggregate and grading and amount of asphalt, regardless of consistency, within quite wide limits. These test results were considered by many as evidence that the Stabilometer test was not consistent, as it was presumably an accepted fact that asphaltic concrete was of higher quality and therefore more stable than an oil mix pavement, for instance.

Seeking means to measure the differences which obviously do exist between pavements using light oil and those using hard asphalt, a device was built to measure the tensile strength or cohesion of the mass. The tensile strength of a bituminous pavement is, of course, due to the adhesion of the asphalt to the aggregate particles, and the cohesive strength of the bituminous films.

It was soon found that definite and consistent differences could be measured between oils and asphalts of varying consistency. A given specimen with "D" grade asphalt may have as much as 50 times the strength of a mix using fuel oil.

An attempt to correlate tensile strength values with pavement performance shows very uncertain agreement. The fact that mixtures of very low tensile strength can and do remain smooth under traffic, and also that mixtures of quite high tensile strength have been known to become waved and rutted, is proof that this quality is not essential for resistance to the distorting effects of vehicle traffic.

It is, however, true that if the pavement is sufficiently lubricated unstable so as to have a tendency to distort under traffic, the time required for roughness to become evident will depend to a great degree on the tensile strength or rate of flow of the bitumen serving as binder.

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J. W. Powers, "A Method of Testing to Determine the Suitability of a Material for Oil Treatment," "Arizona Highways," June, 1930.

2. A. R. Ebberts, "Emulsifying Effects of Asphalt Fillers," "Rock Products," Vol. 35, Nov. 22, 1930, pp. 53-55.

3. The following is quoted from a summary of replies to a questionnaire sent out by the Nevada State Department of Highways in 1930. The section quoted below is from the reply sent in by the State of Washington.

"(3). Oils lighter than 95% gave lower stability in direct ratio as the asphalt content, keeping the percent of bitumen in the mix constant; but for a given grade of oil stability increased as the percent of bitumen in the mix was increased. This latter was true even beyond percentages desirable for use from standpoint of bleeding or shoving on the road.
"(4). For different brands of oil of the same grade there is practically no difference in adhesiveness as shown by stability tests using standardized aggregate.
"(5). Stability tests performed on material from 60-70 oil roads giving good service were so low, even at 70 degrees, as to be meaningless. The advantage of such oil must therefore lie in its ability to resist emulsification in wet weather."

4. H. W. Skidmore, A. S. T. M. Technical Papers, 1924, Vol. 24, Page 950. The following quotation from Skidmore is taken from a discussion in which Mr. H. B. Pullar proposed the use of air-blown asphalts.

"The theory which he (Mr. Pullar) seems to be proceeding on, starts from the premise that the

4. (Continued)

asphaltic binder is the primary desideratum so far as the structural stability of the paving mixture is concerned. Such a conception is not the correct one and will only lead to trouble with the mixtures. For many years such a theory regarding asphaltic pavements has existed in the minds of a great many engineers and paving experts but actual results under modern traffic conditions, together with extensive research of mixtures during the past few years, have demonstrated beyond a single doubt that this theory is erroneous. The character of the bitumen used as a binding medium has, of course, some effect upon the serviceability of the mixture. However, according to the fundamentals of mixture designing, we are building structures composed of mineral aggregates in a mass, cemented together by means of a 'glue' which, in the case of asphalt mixtures, is asphaltic cement. By a proper selection of aggregate materials, the voidage may be reduced to an absolute minimum, requiring in consequence the minimum of binder, which means that the thickness of the film of binder surrounding the particles is very much reduced from that which obtained in paving mixtures laid under the practice as it existed until recently.

"By such proper attention to aggregate grading, modern mixtures are developed which produce surprising strength and stability almost regardless of the exact nature of the binder, again demonstrating that the problem of stable mixture design, to produce pavements able to withstand the displacing effect of heavy traffic, resolves itself into that of the proper selection of aggregates to produce maximum density or low voidage and, after reaching this condition, using just enough bitumen to bind the particles together, that is, approximately that required to fill the voids. This conception of mixture designing reduces to rather a secondary position the asphaltic material itself. In fact, it can be shown by actual laboratory results that pavements of vastly superior structural strength can be produced by this conception of design, using asphalts of so much greater softness than is now common practice, as to be almost startling. For example, it can be shown that the use of asphalts of 100 or more penetration at 77°F. will produce mixtures of several times the tensile strength of normal mixtures according to the old theory in which comparatively hard asphalts of, say, 40 penetration were used."

5. G. H. Perkins, A. S. T. M. Technical Papers, 1925, Vol. 25, Page 370.

"The average vehicle is in contact with the surface continuously and in passing over any one spot imposes on that spot, not impact, but a strain which rises from zero to a maximum and decreases again to zero almost instantaneously. The pressure of the wheel tends to push the mixture forwards and sideways but not backwards."

6. W. J. Emmons and B. A. Anderton, "Temperature as a Factor in the Stability of Asphaltic Pavements," "Public Roads," April, 1926, Page 46.

W. J. Emmons, "Stability Experiments on Asphaltic Paving Mixtures," "Public Roads," January, 1934.

7. H. M. Milburn, "Deformation Tests for Asphaltic Mixtures," "Public Roads," August, 1925, Page 131.

8. A. T. Goldbeck and M. J. Bussard, "The Supporting Value of Soil as Influenced by the Bearing Area," "Public Roads," January, 1925, Page 1.

9. Professor E. C. Bingham, "Fluidity and Plasticity," Page 262-3.

"The laws of solid friction may be stated as follows: (1) When two unlubricated smooth surfaces slide over each other, the frictional resistance P varies directly as the load W or

$$P = k W \qquad (111)$$

and the coefficient of friction k is defined as the ratio between the friction and the load.
2. The force P_0 required to maintain an indefinitely small rate of shear, the so-called <u>static friction</u>, is greater than when the rate of shear is appreciable. The dynamic friction is independent of the velocity.

9. (Continued)

3. The friction is independent of the area of the surfaces in apparent contact, within wide limits. The surfaces must, however, be large enough so that the surfaces remain intact.

"Since it is impracticable to obtain a pair of smooth and entirely unlubricated surfaces, it is needless to say that these laws are very inexact. As already intimated, well-fitting and clean surfaces of similar material would probably seize and follow the laws of plastic flow, which are very different from the laws given above. They have, however, both historic interest and practical usefulness.

"Just as the laws of solid friction are superficially unrelated to the laws of plastic flow, so these laws are also in sharp contrast to the laws of viscous flow which apply to well-lubricated surfaces. With well-lubricated surfaces we have the relation

$$P = S\eta\frac{dv}{dr}$$

where S is the area of surface in contact, dv is the velocity and dr is the thickness of the oil film. According to this relation:

1. The frictional resistance P is independent of the load.

2. The friction is directly proportional to the velocity and is therefore zero when the velocity is zero.

3. The friction is also directly proportional to the area of surfaces in contact.

In view of the absolute antithesis between these two sets of laws, it is not surprising that the results of the study of friction as recorded in the literature are often contradictory. We may, however, state broadly that slow-moving, poorly lubricated surfaces follow approximately the laws of solid friction, whereas rapid-moving and hence necessarily well-lubricated machinery, such as electric dynamos and motors, follows the laws of fluid friction. Most bearings are imperfectly lubricated and follow neither set of laws exactly."

10. W. J. Emmons and B. A. Anderton, "Temperature as a Factor in the Stability of Asphaltic Pavements," "Public Roads," April, 1926, Page 46.

11. Clerk Maxwell, "Theory of Heat."
(Quoted from "Fluidity and Plasticity," Page 215-6)

"If the form of the body is found to be permanently altered when the stress exceeds a certain value, the body is said to be soft or plastic and the state of the body when the alteration is just going to take place is called the limit of perfect elasticity. If the stress, when it is maintained constant, causes a strain or displacement in the body which increases continually with the time, the substance is said to be viscous.

"When this continuous alteration of form is only produced by stresses exceeding a certain value, the substance is called a solid, however soft it may be. When the very smallest stress, if continued long enough, will cause a constantly increasing change of form, the body must be regarded as a viscous fluid, however hard it may be.

"Thus a tallow candle is much softer than a stick of sealing wax; but if the candle and the stick of sealing wax are laid horizontally between two supports, the sealing wax will in a few weeks in summer bend under its own weight, while the candle remains straight. The candle is therefore a soft (or plastic) solid, and the sealing wax is a very viscous liquid.

"What is required to alter the form of a soft solid is sufficient force, and this, when applied, produces its effect at once. (This is, of course, only relatively true, because plastic deformation is a function of the time, as will appear later.) In the case of a viscous fluid, it is time which is required, and if enough time is given the very smallest force will produce a sensible effect, such as would be produced by a very large force if suddenly applied.

"Thus a block of pitch may be so hard that you can not make a dent in it with your knuckles; and yet it will, in the course of time, flatten itself out by its own weight and glide down hill like a stream of water."

12. G. H. Perkins, A. S. T. M. Technical Papers, Vol. 25, Page 371-2

"For instance all of these tests measure the effect of a compressive load increasing at a definite rate, from zero up to the load required to

12. (Continued)

cause a shear or flow within the mixture. Such a method of loading may be applicable for determining the type of mixture which will best withstand the effect of standing vehicles, but the traveling public is more concerned with deformations in the traveled way, and to measure the effect of moving vehicles I think we need a test which is somewhere between impact and static load.

"While it is true that when a motor truck running along a bituminous pavement which had started to wave, does jump, the wheels leaving the pavement and then striking it, giving pure impact, the wheels of the average automobile do not. Again while the impact of a heavy motor truck unquestionably damages the foundation and thereby produces deformations in the pavement as a whole by depressing surface and foundation together, I question whether it often causes deformation within the surface mixture itself.

"The average vehicle is in contact with the surface continuously and in passing over any one spot imposes on that spot, not impact, but a strain which rises from <u>zero to a maximum and decreases again to zero almost instantaneously. The pressure of the wheel tends to push the mixture forwards and sideways but not backwards.</u>

"For instance, many bituminous roads under medium weight traffic--that is, with not very many motor trucks, but mostly pleasure automobiles--will remain perfectly smooth for two or three years and then suddenly in a hot spell start to wave or produce a washboard. In other words, <u>the deformation is the accumulated effect of an enormous number of small instantaneous loads or pushes.</u>

"I think you will find, also, that in any wide street without car tracks the deformations are on the quarter, largely due to the side-thrust of traffic. The pavement is being pushed forward and at the same time is being pushed over toward the gutter. These deformations do not always appear directly under the spot which is struck by the traffic. For instance, I remember seeing the effect of the first set of traffic tests at Arlington, described by Mr. Anderton, where in many cases the bituminous-concrete mixture had been pushed forward several feet, yet a straight edge laid in the line of traffic showed no vertical deformation at all. On the other hand, the pavement about a

12. (Continued)

foot to one side of the wheel tracks showed a ridge several inches high, but practically no lateral movement."

(The underlining is my own.)

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